Measuring transient voltages between separate ground points

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How many times have your circuits been bitten by ground loops or induced voltages on the system ground plane? Knowing how to make scope measurements of ground potentials can put your circuit on a fast road to recovery.

Textbooks apply the phrase "circuit ground" to a reference potential from which you can measure relative voltages. In practice, however, no two points on a circuit's ground plane are exactly at the same potential, and they generally exhibit a nonzero impedance between them. Overlooking this fact in the presence of the transient ground currents common in today's high-speed digital circuits can lead to circuit problems that are difficult to analyze and troubleshoot. Three scope methods offer pros and cons to characterize these potential differences by measuring the voltage between separate ground points.

Digital circuits respond to the potential difference between an input signal and the ground potential measured on the die. If there is sufficient inductance between the die and the package pins, the transient voltage between the die's ground potential and the ground potential at the pin can be significant. The notorious ground-bounce effect in high-speed CMOS circuits is a good example.

The problem is further exacerbated by inductance in the trace that connects the ground pin to a ground plane on the pc board (**Fig 1**). An additional potential difference is due to the inductance of the ground return between the pc board's ground plane and the power supply's ground. Essentially every ground conductor has inductance, and rapidly changing ground currents will induce a transient voltage in the conductor according to $E_{ind} = L \times di/dt$.

Suppose you're scratching your head because a gate or a flip-flop changes state when there is no appropriate change of input signal. The enigma may be resolved if you consider the IC's ground as one of the input signals. Remember the IC responds to the potential difference between an input pin and its ground pin; voltage changes on either pin affect the circuit the same way. To ascertain if a glitch or metastable state is caused by an induced ground potential, you need to be able to measure the voltage difference between two separate points on the ground plane.

To measure the voltage across a low-resistance path when there is no absolute ground reference, you must make a differential measurement between the two points. One method is to use a dual-channel oscilloscope and two probes of the same type. You connect one probe to one point on the ground path in question and

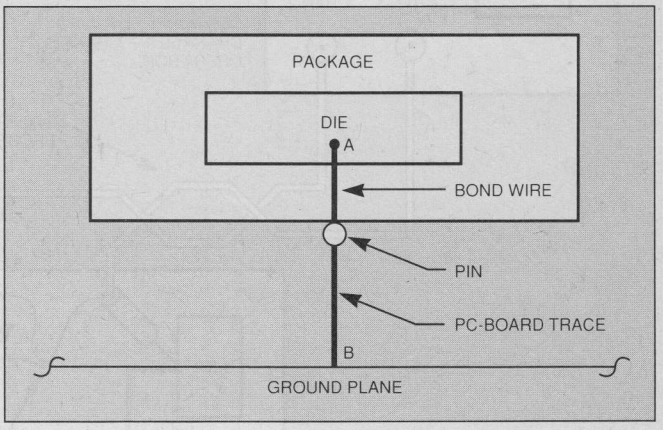

Fig 1—The ground potential at point A on a die can be different from the potential at point B on a pc board's ground plane. The inductance of the bond wire from the die to the package pin and the inductance of the pc-board trace from the pin to the ground plane induces a transient voltage when there are rapidly changing ground currents.

the other probe to another point on the ground plane. You then subtract the signals for each channel using the scope's A – B feature.

To make reliable measurements, you must minimize the time skew between each channel, including the probes. To de-skew the probes, you can follow the recommended procedures in the operator's manual, but generally only digitizing oscilloscopes let you adjust time skew between channels. If you use an analog oscilloscope, you must use probes that have well-matched time delays. The Tektronix Model P6135A matched pairs of probes are good examples.

The gains of the two channels and the two probes must also match. Most digitizing scopes have a probe attenuation factor that lets you match the probe and channel gains. You connect both probes to a common signal, set the scope for A – B operation, and adjust the probe attenuation factor on either channel for minimum deflection on the display. On an analog scope, you can use the vertical sensitivity vernier on either channel to balance the gains. Some digitizing scopes have a continuously variable vertical sensitivity, which lets you match the gains.

If you use 1- or 10-MΩ style probes that need to be frequency compensated, be sure to carefully adjust the compensation on each probe. Any mismatch in the probe's compensation can lead to severe degradation of the common-mode rejection at high frequencies. Connect the probe grounds using a short wire and then connect the center of this wire to a ground point in the system under test.

Because the system ground point can affect the test results, you should choose it with some care. Ideally, the system ground point should not experience a current transient that coincides with the induced voltage transient you are trying to measure. A sheet-metal ground or a board-mounting screw near the measurement point is often a good choice. It's also a good idea to intertwine the two probe cables to minimize electromagnetic coupling to the probe shields (**Fig 2**).

A low-resistance divider probe, such as the HP54006A or the Tektronix P6150, is generally the best probe for making dual-channel differential measurements. The HP54006A probe has a flat frequency response and a bandwidth of 6 GHz. Although the divider probe has a minimum input impedance of 450Ω, resistive loading is negligible because the measurement is being performed on a low-impedance circuit.

There are some inherent inaccuracies in dual-channel measurements, but a few procedures can help you minimize them. One useful technique to evaluate errors caused by ground loops or induced transient voltages at the system ground point is to short the tips of the probes together and disconnect them from the system under test. Observe the scope to see if there are any deflections on the display. If so, move the system ground to another point and try to find a point that minimizes the deflection on the display. In some in-

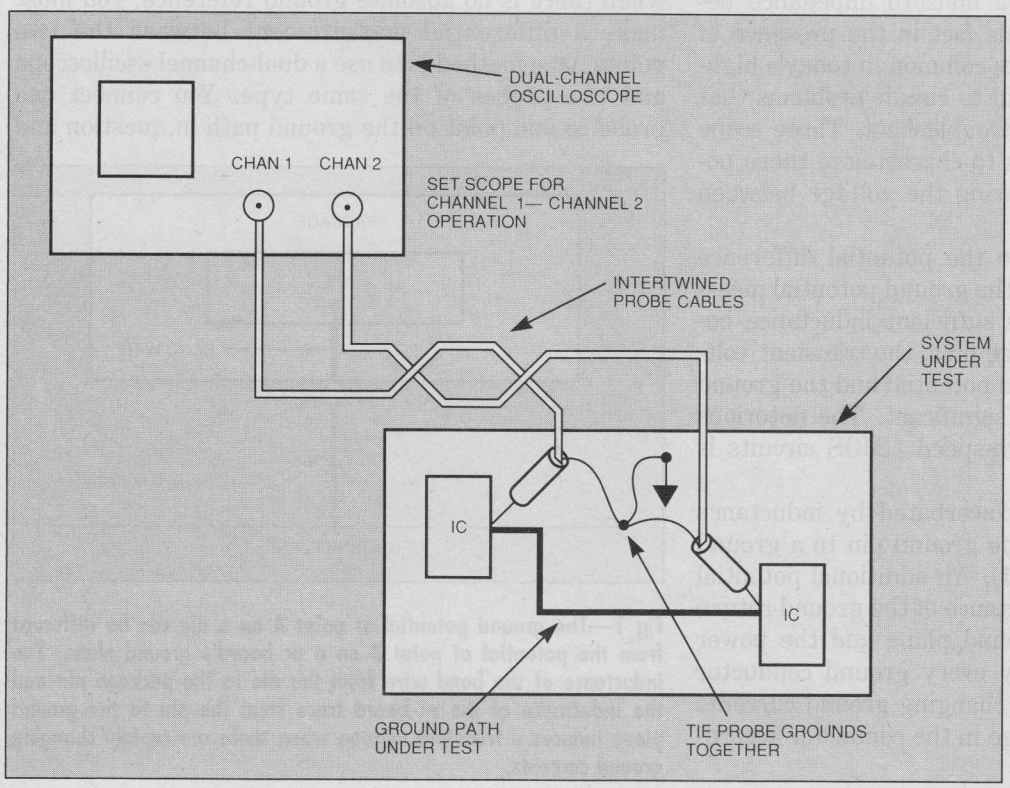

Fig 2—When using a dual-channel scope, connect the two scope ground probes and connect a short wire at the center point to a convenient ground in the system under test. Intertwining the probe cables minimizes electromagnetic pickup.

stances, it may be best not to connect the probe shields to the system ground point. The probe tips must be shorted together to determine this, however.

Other potential sources for measurement error are ground loops formed by the probe shields and the scope ground (**Fig 3**). All ground loops are susceptible to pickup voltages caused by circulating electromagnetic fields. If you use 1- or 10-MΩ compensation-type probes, the input capacitance from the probe tips to the shield and the scope's input-channel capacitance creates ac ground loops. You can minimize the susceptibility of these loops to electromagnetic pickup by intertwining the probes together.

During measurement, each probe is subject to complex electromagnetic and electrostatic fields. Because the two tips are at different locations, the field coupling is different. The signal you observe on the display is not only the actual voltage difference between the measured points, but also the difference in the electromagnetic and electrostatic coupling at the probe tips.

Inaccuracies caused by coupling differences are hard to evaluate and difficult to control, but usually are small enough to ignore. You can test for this coupling effect by moving the probe cables around and observing changes in the scope display. The further apart the measurement points are, the more pronounced the problem is. Another difficulty can arise when the scope can't trigger on the difference signal. Usually triggering the scope on one of the signal channels overcomes this difficulty.

A differential probe, such as the HP 1141A, gives you a second method for making differential voltage measurements. Differential probes provide high sensitivity and excellent common-mode rejection for frequencies as high as 100 MHz. In addition, differential probes eliminate the concern of having two probe shields forming a large loop. You don't have to frequency compensate, time de-skew, or match the gains when using differential probes. Thereby you eliminate these sources for error. Differential probes also let you trigger the scope on the differential signal.

The differential-probe method presents some other difficulties, however. For one, the probe tips on a differential probe are physically close together. If you must make a differential measurement at two points that aren't close together, you must extend the lead lengths of the probes, which adds significant inductance or capacitance. Extending the lead lengths increases the size of the loop that is subject to electromagnetic pickup.

The bandwidth of a differential probe is considerably less than that of a resistive divider probe. For example, the HP 1141A bandwidth is 200 MHz, compared to the 6-GHz bandwidth for the HP 54006A divider probes. You still must determine where or whether to connect the differential probe's ground to the system under test. Similar to the dual-channel method, you must short the inputs of the probe together and determine the optimum grounding point by minimizing the residual signal on the display.

If you have the luxury of owning a digital-storage scope, a third method for making differential measurements is often the most accurate. This method uses only one probe to store digitized data from two points into waveform memory and then perform waveform mathematics to calculate a difference waveform. The procedure is:

1. Measure the waveform at one point and store this data into waveform memory.
2. Measure the waveform at the other point using the same probe and the same scope channel. Don't move the probe's ground connection to the system under test. Store the data into another portion of waveform memory.
3. Use the scope's waveform math capability to subtract the data for the two waveforms stored in memory. The scope will automatically calculate the difference and display the waveform.

If you use the third method, you should adhere to the same precautions concerning the probe shield's connection to a system ground point as in the first two methods.

There are several reasons why the third method is more accurate than the other two. For one, you use

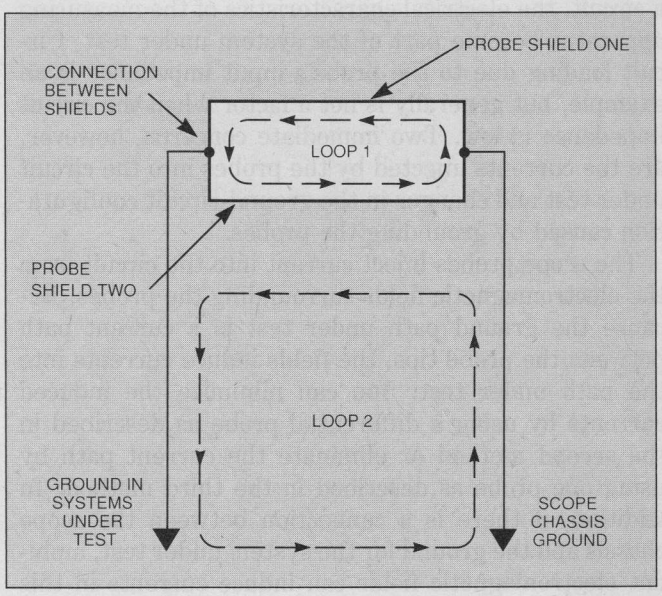

Fig 3—In a dual-channel measurement, the two probe shields form a loop, which can pick up induced currents caused by electromagnetic fields. The connections of the probe shields to the scope-chassis ground and to the ground in the system under test form an additional loop that is susceptible to pickup.

the same probe and scope channel for collecting data from two points. Therefore, there are no errors caused by mismatches in gain, frequency response, or time delays. Because there is only one hook-up from the probe shield to a system ground point, there is no loop formed by two probe shields as there is in the first method mentioned. Also, because the probe tip only measures one point at a time, the ground strip under test doesn't complete a loop, which could pick up induced currents from changing electromagnetic fields.

If you use the third method, you should be aware of a couple of its idiosyncrasies. Unlike the first two methods, the probe loading for the system under test is not balanced. The probe only loads one point at a time. However, because the ground trace under test has a low impedance, the unbalanced load is not a significant problem. In addition, if the physical distance between the two points is long or the system ground point is far removed from the trace under test, the wire connecting the probe shield to the system ground will be long. The inductance of the long lead can cause ringing and electromagnetic pickup. Theoretically, the ringing and pickup should cancel when the scope subtracts the two waveforms. However, the induced voltages caused by the electromagnetic fields surrounding the probe and the ground lead will change when you move the probe. Therefore, the waveforms may not exactly cancel.

Regardless of which method you use, you should be aware of some details that are common to any circuit measurements. Anytime you make a measurement on a circuit, the electrical characteristics of the measuring apparatus become part of the system under test. Circuit loading due to the probe's input impedance is an example, but generally is not a factor when the circuit impedance is low. Two immediate concerns, however, are the currents injected by the probes into the circuit under test and changes in the ground-circuit configuration caused by grounding the probes.

The scope probes inject current into the circuit from the electromagnetic fields surrounding the probes. Because the ground path under test is a current path between the probe tips, the fields induce currents into the path under test. You can minimize the induced currents by using a differential probe as described in the second method or eliminate the current path by using one probe as described in the third method. In addition, if there is a connection between the scope chassis and the ground for the system under test, ambient electromagnetic fields can induce currents in this ground path.

Another reason for current injection is a potential difference that may exist between the scope chassis and the ground for the system under test. Potential difference causes a current to flow between the scope and the system under test through the probe shields and the probe's ground wire. In addition, some current may also flow through the probe tip to the circuit under test. If you use a low-resistance divider probe, such as the HP 54006A, the 450Ω tip resistor limits the current to a negligible value. However, if you use a 1- or 10-MΩ compensation-type probe, current can flow into the circuit through the probe's compensation capacitor, which has a low impedance at high frequencies.

When you connect the scope's ground to the system under test via the probe-shield ground, make sure you don't modify the current path for the ground trace under test. Make sure you don't select a ground point that is directly in the path you are measuring. If the system has separate analog and digital grounds, you should choose an analog ground point when you are measuring a ground potential in the digital section and a digital ground point when measuring a ground potential in the analog section.

Although following these guidelines will increase your confidence in the accuracy of a measurement, it's impossible to set up exact recipes to follow. The best method depends on the particular situation. You should understand the basic principles that cause ground potentials to exist in your specific ground system. As a reality check, you should make measurements using at least two of the methods. If you obtain inconsistent results, one of the methods is probably invalid. Remember, however, arbitrary high accuracy cannot always be attained. EDN

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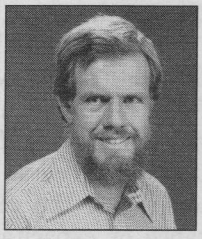
Author's biography



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